A Survey of Geospatial-Temporal Visualizations for Military Operations

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Abstract: European defense funding has surpassed 200 billion euros per year for the first time, with a renewed strategic interest in creating technological innovations that aid military cooperation, such as comprehensive decision-support systems. Overcoming the many challenges associated with the research and development of such military technologies presents an excellent opportunity for the visualization community's contributions in the domain, as there is ample scope for applied research. No other recent surveys examine the use and design of Information Visualization (IV) and Visual Analytics (VA) tools in the military domain. As such, this survey's primary interest is to investigate and assess IV and VA tools' functionality and integration into military decision-support systems, specifically focusing on geospatial-temporal visualization aspects. Considering this objective, this survey systematically identifies and discusses suitable visualization solutions and the benefit they may offer to military decision-support systems through the lens of the *Military Operations Process*. This results in a domain-specific design space for analyzing various existing and relevant military products. This survey's outcome and main contribution is thus the formulation of a design space and analysis of existing military products. This leads to identifying gaps, opportunities, and guidelines for where geospatial-temporal visualizations in military decision-support systems can enhance military commanders' decision-making capabilities and ability to act.

1 INTRODUCTION

The Russian invasion of Ukraine has escalated the risk of a spillover war with a NATO member, resulting in 18 European countries increasing military spending in 2022. The European Defence Agency has stated, *"co-operation must now become the norm"* (Quinn, 2022), calling for the increased need to develop emerging military technological capabilities as a necessary intervening variable to handle both conventional and unconventional future warfare (Leuprecht, 2019). To counter these modern threats, many armed forces have re-emphasized and re-prioritized compatibility and interoperability across military equipment, with a desire to create common, open-source, integrated, and secure military technology platforms which easily enable cross-platform interactions. Further development of such emerging military technologies requires overcoming a myriad of challenges posed by the research, development, and implementation of such technologies. Yet, it can be an opportunity for the visualization community to contribute to the abundance of research projects in this domain.

Examples of such related challenges are many, as described in (O'Hanlon, 2018), and include the development of software for overcoming the threat of cyber-warfare by devising new novel tools which make it easier to monitor, analyze, detect, and respond to unauthorized activity, the implementation of artificial intelligence (e.g., for route-planning analysis (Lazarowska, 2022)), the possibility of analyzing multi-source military intelligence data using natural language processing (Hecking et al., 2011), and the development of augmented reality (AR) technologies (Le Roux, 2010) to improve commanders' and soldiers' situational awareness. Despite the many challenges this domain is confronted with, innovations in defensive technologies can be worthwhile pursuits as they can benefit and permeate many domains as well as the general public. An example of such a defensive technology that evolved into universal use is the internet which began as a modest research exper-

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iment to link three early packet networks in an open-architecture framework (Kahn et al., 1997).

In this context, there is also a particular contemporary interest in supporting the functionality of new and existing military decision-support systems by integrating Information Visualizations (IVs) and Visual Analytics (VA) tools with advanced Graphical User Interfaces (GUIs), producing *Visual User Interfaces* (VUIs) that can support and improve well-informed decision-making capabilities (Tardy, 2020).

The interest in developing such systems is prevalent as military operations are intrinsically complex and dynamic by nature. As such, they call for visualizations implemented in an equally sophisticated and advanced manner to support well-informed decision-making. In this survey, we examine and discuss geospatial-temporal visualization solutions and the benefit they may offer to military operations. In this context, we aim to identify prospective areas of future visualization research, including elaborating on the research prospects of innovative technologies such as AR, micro-visualizations, and 4D representation of geospatial-temporal data for military purposes.

No other *recent* surveys examine IVs and VA tools used in the military domain, with only Gouin and Evdokiou (2004) exploring the area. This survey thus aims to provide an analysis of recent visualizations used in the military domain to derive guidelines that could be used in the design process of visualizations and VA tools supporting military operations, relating visualizations to the *Military Operations Process* (NATO Standardization Office (NSO), 2019b).

To outline the contents of the survey, we describe the scope and survey methodology in Section 1.1 to narrow the focus. Then, in Section 2, we introduce the relevant military theory and highlight the need for suitable geospatial-temporal visualizations in successfully carrying out military operations.

In Section 3, we emphasize how domain-specific constraints and military standards affect the use and implementation of visualizations in the military domain. Following this, in Section 4, we describe our design space subsequently used for analyzing twenty military products, as shown in Table 1. Then, in Section 5, we discuss patterns such as design and implementation gaps and opportunities identified based on our analysis of military products. Finally, we conclude our survey findings in Section 6.

1.1 Scope

The related works examined were limited to those of an unclassified nature to promote accessibility and reproduction. This survey assesses academic literature on military operations, situational awareness, knowledge and insight generation, human-computer interaction, and visualization techniques. This theory is then framed based on state-of-the-art examples in current decision-support systems from product manuals/videos/images, design guides, military standards, tech reports, and knowledge of military operations.

Survey Methodology: We searched for related products and publications within the given survey scope. We utilized Google Scholar to browse visualization, military theory, situational awareness, and knowledge and insight generation using relevant keywords like "military visualization" or "geospatial-temporal visualization" to gather academic references. Reviewing each paper's related works and sections individually, we traced every cited reference and checked if it fitted our survey scope. In addition, we used Google Search to find twenty relevant military products that applied visualization and were suitable to be examined in our survey. We also browsed military standards, manuals, and tech reports through NATO's Standardization Office's archive[1] and military standards aggregator EverySpec[2].

2 BACKGROUND

Military organizations, commanders, and subordinates have put forward higher requirements for accurate and prompt information transfer through various IVs, VA tools, and GUIs during the planning, execution, and assessment of military operations.

Military operations are coordinated actions conducted under dynamic and uncertain conditions to achieve objectives for a particular purpose. These actions involve various tasks carried out by different categories of military personnel, which we identify as:

Commanders: A category of military personnel who command and control military forces and who are involved in making decisions to achieve goals that ultimately place military forces in the desired end state. Commanders work at a strategic level.

Military forces: The military personnel carrying out the commanders' orders and instructions. Military forces "on the ground" work at a tactical level.

Intelligence data that military organizations can gather primarily relates to time (a temporal dimension) and space (spatial dimensions) along with actors

[1] https://nso.nato.int/nso/nsdd/main/standards
[2] http://everyspec.com/search_result.php

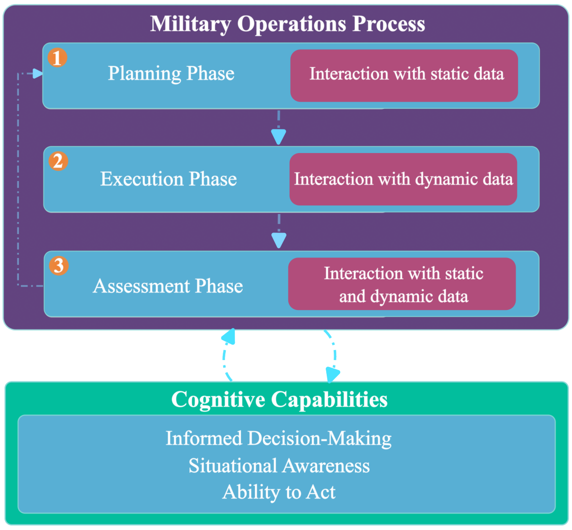

Figure 1: A depiction of how visualization can be used in the cyclic *Military Operations Process* to increase situational awareness, decision-making, and ability to act by improving commanders' cognitive perception.

(e.g., people) and objects (e.g., facilities and equipment) and the events that they generate.

The execution of military operations requires situational awareness at all levels, from the strategic to the tactical. A general definition of situational awareness is provided by Vidulich et al. (1994) which states situational awareness is the *"continuous extraction of environmental information, integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception and anticipating future events"*. As such, employment of suitable geospatial-temporal visualizations is critical as a means of achieving the goals as set out in the the military operations process.

We define the military operations process as consisting of central command and control activities performed during military operations, namely planning, execution, and assessment, as depicted in Figure 1 (Department of the Army (DA), 2019). The military operations process can be complex and vary depending on the operations' scale, scope and context. Furthermore, the different phases of the operations process typically overlap and recur as circumstances demand. However, at all times, commanders drive the operations process, by applying critical and creative thinking and building and maintaining situational understanding by encouraging collaboration and dialogue. Each phase of the operations process consists of a chain of high-level tasks, each with a different emphasis on information visualization and interaction requirements. Therefore, we separate the phases to highlight each phase's prominent theme to more easily discuss the various requirements and visualization techniques that may be appropriate. The phases and the themes of each, are described as follows:

1. Planning of the operation according to known and established goals and objectives. In the planning phase, emphasis is placed on the interaction with static data (all data known at the current point in time) through IVs that relate to the representation and simulation of geospatial-temporal data associated with the conception of military operations.

2. Execution of the operation by carrying out planned actions. In the execution phase, the accentuation of IVs used is placed on those which support the monitoring of dynamic (new incoming real-time) data, such as, information regarding moving geospatial-temporal objects and streaming time-series data. Furthermore, the execution phase also relies on the effective communication of initial orders and information from a commander at a strategic level to subordinates at a lower tactical level and vice versa.

3. Assessment of the operation, along with reporting and documentation for future use and analysis. The assessment phase is predominately concerned with IVs depicting insights derived from static and dynamic data, such as, completing goals, identifying trends, and providing reflections on military operations. These all feed into the next iteration of the military operations process.

Visualization & Military Operations: Military operations require VUIs implemented in a sophisticated manner to reduce cognitive load, promote well-informed decision-making and provide constant situational awareness. Proper VUIs facilitate and assist military commanders in successfully carrying out and correctly perceiving numerous high-level tasks such as collaboration, communication, interoperability, reconnaissance, surveillance, and target acquisition while carrying out military operations. VUIs support the success of such high-level tasks by allowing actions (Munzner, 2014) in relation to the military operations process (NSO, 2019b; DA, 2019).

Visualization at the Strategic Level: Decision-support systems support military operations. In this context, Command and Control (C2) systems[3] are a particular type of decision-support system that embody the operations process and relay a Common Op-

[3]Many derivative terms exist and emphasize different aspects, uses, and subdomains of C2. The abbreviations associated with these terms are numerous. We thus find it sufficient to use C2 as a catch-all term.

erational Picture (COP) to various categories of military personnel.

Commanders in a command center maintain an overview by consuming the information processed and managed by the C2 system. Commanders consume the information to drive the operations process through direct manipulation and interaction with the information managed by the C2 system. VUIs used in this setting operate at the strategic level and are used by personnel in a remote site (e.g., a command center). Such VUIs facilitate the coordination and communication of information to subordinates at a lower tactical level.

Visualization at the Tactical Level: VUIs used at the tactical level are used by personnel ”on the ground” (e.g., pilots, soldiers, divers). In this context, physical constraints limit the possibilities concerning what is and can be visualized and interacted with in a VUI. The most prominent challenges associated with VUIs at this level, relates to constraints such as space limitations, light conditions, and limitations related to operating the interfaces on the move (Motti, 2020).

3 DOMAIN SPECIFIC CONSTRAINTS/STANDARDS

Many domain-specific constraints are associated with implementing geospatial-temporal visualizations for military purposes. The constraints that apply should be considered when implementing visualizations in military decision-support systems. These include environmental conditions, display size, workspaces, the possibility to organize and arrange windows, and the design of graphical interface components.

3.1 Environmental Constraints

The various environments within which military operations occur directly limit equipment’s capabilities, affecting how a VUI should be designed to ensure optimal usability. To overcome this, VUI components need to be designed in a specific way to compensate for the degraded viewing or operational conditions that may exist in the environment, as shown in Figure 2. When carrying out design within such constraints, it is vital to assess several factors, including:

- Display readability and force visibility
- A display should not create visual fatigue or loss of coordination
- External environmental factors should be incorporated into design

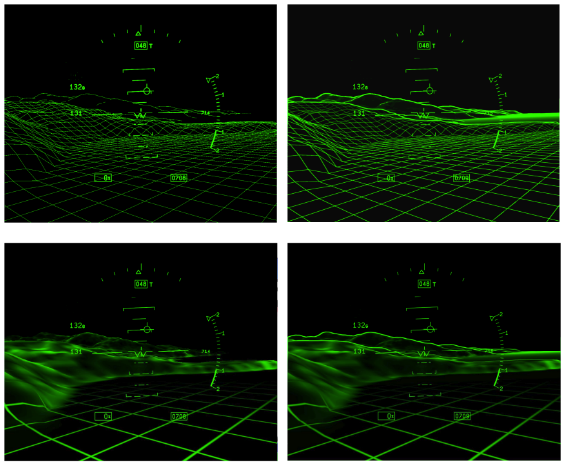

Figure 2: Example of a synthetic vision system used in head-mounted devices for military pilots. The system allows permanent perception of the terrain and obstacles around the aircraft, through direct and synthetic views, even in poor visibility conditions. Source: (Lemoine et al., 2013).

- Equipment should be highly shock and vibration-resistant (United States Navy, 1989; U.S. Department Of Defense (DOD), 1969)

3.2 Displays

3.2.1 Large Displays & Video Walls

Current Implementations: Video walls are used at a strategic level in military operations. They consist of multiple smaller high-resolution screens (with minimal bezel) placed together to give the impression of one large display, typically larger than 60 inches. Higher command usually uses them in centralized command rooms in indoor conditions. The additional real estate that video walls provide enables commanders to view a ”whole picture” of operations as the level of representation of IV is much greater.

Potential Implementations: It has been studied in the visualization literature whether visualizations for larger displays need to be fundamentally different from visualizations on standard desktop displays and whether basic visual design principles are different for large displays. For example, in the work by Andrews et al. (2011), an extensive list of visualization design guidelines for large displays has been derived. Based on these guidelines, the authors conclude that designing visualization for larger displays is not simply a matter of scaling up existing visualizations or displaying more data. Instead, they conclude that visualization designers need to adopt a more human-centric perspective and highlight the importance of physical navigation in how the user will approach,

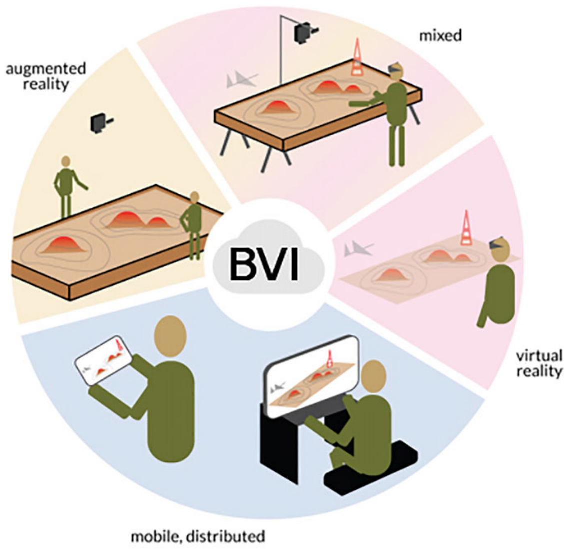

Figure 3: Example of Battlespace Visualization and Interaction (BVI) types illustrating augmented reality, virtual reality as well as mobile and distributed, developed for visualizing military operations. Source: (Boyce et al., 2022).

perceive, and interact with visualizations on these larger displays. There is ample opportunity for improved implementation of geospatial-temporal visualizations in these situations, with increasing emphasis on human-centric design and interaction.

3.2.2 Small Displays & Alternatives

Current Implementations: Small or "micro"-displays are typically very small, ranging from around 2 to 10 inches. Tactical forces "on the ground" typically use them to display limited but vital information. As the screen size of these displays is limited, so are the types and amount of visual information they can communicate to a user. Similarly, there are alternative methods of displaying IVs during military operations, as shown in Figure 3 where traditional visualization methods may not be sufficient. These include papers focusing on land (Ferrin, 1999) and the sub-sea environment (Scubapro, 2022), which have investigated the possibility of integrating display devices into tactical helmets in the form of head-mounted/Head-Up Displays (HUDs), to better provide access to situational awareness tools (Le Roux, 2010) while also limiting the effect of the lumination of the display on the soldier or, e.g., diver.

Potential Implementations: Developments for displays in small and head-mounted devices could include improved use of micro-visualizations, Augmented Reality (AR) displays, and feature tracking for military operations. E.g., see how the use of HUDs within the aviation industry to augment a pilot's vision could be applied to a number of military operations, such as sub-sea operations Lemoine et al. (2013). However, developments of such novel technologies are not without their challenges. For example, the Integrated Visual Augmentation System (IVAS) using AR goggles resulted in personnel suffering from nausea, headaches, and eyestrain when using the device (Harding, 2022).

3.3 Windows & Workspaces

The arrangement of a single window or a group of windows on display can be regarded as a user's workspace.

- A single-window workspace is typically displayed on the entire screen, enabling a user to focus on a single task. As a result, a single window workspace is particularly well-suited to smaller screens where display real estate is constricted.
- A multi-window workspace allows multiple windows to be displayed simultaneously on a single display. The windows in the workspace can be overlaid over one another or divided across the display according to a user's needs.

Typically, in decision-support systems designed for military purposes, workspaces designed to be used at the strategic level by commanders are multi-window. In contrast, workspaces intended for use at a tactical level are typically single-window applications.

3.4 Graphical Design

Text & Military Standards: As highlighted by Parnow (2015), carefully considered typography can convey additional information, which may improve VUIs by modifying the visual variables associated with typography. For example, shape (typeface, style, weight, width), position (spacing, indentation, alignment, line spacing), appearance (color, texture, opacity), size (scale), orientation (rotation), underlining, strike-through, etc. can be adjusted to alter its semiotics (Parnow, 2015). The choice of typefaces used in a VUI is typically standardized within military organizations to improve consistency and ensure familiarity and interoperability across organizations (see, e.g., standard APP-56 (NSO, 2018), which specify Arial or Times New Roman as the preferred font). However, a VUI designer can make particular use of, e.g., character spacing, size, and capital letters for typographic coding, headlines, captions, and labels that need special emphasis within this context.

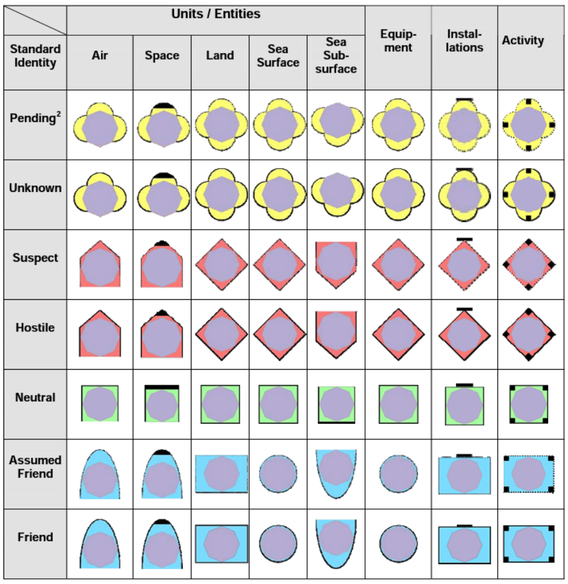

Figure 4: Illustration showing a collection of symbol frames with their associated unit dimension. A solid line is used to denote the certainty of identification of standard identity and shall identify the symbol as representing friendly, hostile, neutral, or unknown actors or objects. Source: NSO, 2019a.

Color & Military Standards: Color as a visual indicator and signifier can be used in military VUIs to convey different yet specific meanings. For example, within military organizations, the colors mentioned next typically have the following meaning: Red means immediate or imminent danger, yellow or amber means caution, outside normal operating limits, system malfunction, or other conditions which can produce hazards in the longer term, green means safe, normal operating condition (Department Of Defense Technical Architecture Framework For Information Management (DODTAFIM), 1996). The coloring of text or a window can furthermore be used to indicate the classification of the information shown in a visualization in an interface (DODTAFIM, 1996).

Particular guidelines exist for military symbology. E.g., the APP-6 standard for NATO military symbology states that all symbol components, except the frame fill, should be the same color (NSO, 2019a). Furthermore, symbol implementations in a VUI must maximize the contrast between symbols and the display background to provide optimum discriminability (Niu et al., 2020). This contrast can be provided by using high-contrast colors for the frame, icon, and modifiers depending on the background and should be incorporated into any kind of visualizations used in military VUIs.

Symbols & Military Standards: VUIs use a variety of simple symbols and icons to help users understand the items, actions, and modes they can choose. In general, icons in VUIs work the best when they use familiar visual metaphors directly related to the actions they initiate or the content they represent. This is especially relevant in small displays and microvisualizations (Isenberg, 2022). Furthermore, symbols and icons for use in military operations in specific IV contexts have been standardized to increase interoperability across nations.

Military symbol standards describe a structured set of graphical symbols to display information in military C2 systems and related applications (NSO, 2019a). The standards serve as a framework for symbol construction by providing a common set of building blocks that can be used to create specific sets of symbols appropriate to particular contexts and settings, as shown in Figure 4.

A proper and robust method of selecting, constructing, and displaying suitable symbology is vital to military VUIs. The correct use of symbols in military operations yields an accurate understanding of the operational picture by commanders. It also helps speed up the decision-making process, as graphical representations of objects, commands, movements, and additional information (including alphanumeric text and colors) can be observed and readily understood faster than just text alone.

4 CLASSIFICATION

Up to this point, we described theory relating to the military operations process and VUI design considerations pertaining to domain-specific constraints and military standards. The following section describes relevant visualization aspects crucial in assessing military products.

This survey is predominantly concerned with geospatial-temporal visualizations used in military products and the domain-specific constraints that affect the visualization of objects and actors at particular points in space and time. We thus describe the most vital aspects related to how VUIs can enhance the performance of military operations through increased human cognition of the COP by appropriately providing information regarding the internal structure of static and dynamic data (intel) and causal relationships within it.

In Table 1, we show our design space and classification system where each column in the top row relates to a corresponding section in this survey, with surveyed military products listed as rows.

Table 1: The tabular analysis of twenty military products according to our established design space. The design space considers the military operations process, domain-specific constraints, and visualizations utilized. ☆ Indicates that the product have the facilities necessary and there is an opportunity for implementation. ✓ Indicates that the product implements the feature.

Example Software		Operations Process					Domain Specific Constraints														Visualizations																
								Ouput Devices				Input Devices									Primary Visualization									Interaction					Collaboration			
																					Map																
	Review Rank	Planning Phase	Execution Phase	Assesment Phase	Strategic Level	Tactical Levels	Environmental Constraints	Video Walls	Standard Displays	Small Displays	Alternative	Keyboard / Mouse	Touchscreen	Bezel Keys	Alternative	Single Window	Multi Window	Text & Military Standards	Color & Military Standards	Symbols & Military Standards	Map Primitives	Map Overlays	2D, 3D, or 4D	Spatial Comparisons	Timelines	Alternative	Data Glyphs	Word-scale Visualization	Secondary Visualization	Map-based Interactions	Visualization Linking	Information Dashboards	Focus+Context	Co-located & Synchronous	Remote & Synchronous	Co-located & Asynchronous	Remote & Asynchronous
Command and Control (C2) Systems:																																					
Lockheed Martin Corporation (C2BMC System)	20	✓	✓	✓	✓			✓				✓	☆		☆		✓	☆	☆	☆	✓	✓	☆	☆	☆				✓	✓	✓	✓	☆	✓	✓		
Battlegroup Command and Control Trainer (BC2T)	19	✓	✓	✓	✓				✓			✓					✓	☆	☆	☆	✓	✓	☆	☆	☆				✓	✓	✓	✓	☆	✓			
Boeing Joint All Domain Command and Control	17	✓	✓	✓	✓			✓	✓			✓					✓	☆	☆	☆	✓	✓	☆	☆	☆				✓	✓	✓	✓	☆	✓	✓		
Saab AB 9Land Battle Management System (BMS)	10	✓	✓	✓		✓	✓		✓				✓	✓		✓		✓	✓	✓	✓	✓	2D	☆	✓				✓	✓	☆	✓			✓		
General Dynamics Corporation (TAIS)	11	✓	✓	✓	✓		✓	✓	✓			✓	✓		✓	✓	✓	☆	☆	☆	✓	✓	3D	☆	✓				✓	✓	✓	✓			✓		
General Dynamics Corporation (IMPACT)	9	✓	✓	✓	✓			✓	✓			✓					✓	☆	☆	☆	✓	✓	3D	✓	✓				✓	✓	✓	✓		✓	✓		
General Dynamics Corporation (GeoSuite)	8	✓	✓	✓		✓	✓		✓	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓	3D	☆	✓				✓	✓	✓	✓			✓		
Terma Maritime Misson System	7	✓	✓	✓	✓		✓	✓	✓			✓					✓	✓	✓	✓	✓	✓	2D	☆	✓				✓	✓	✓	✓		✓	✓		
Thales Group C2 Headquarter	12	✓	✓	✓	✓			✓	✓			✓					✓	✓	✓	✓	✓	✓	2D	☆	✓				✓	✓	✓	✓		✓	✓		
Thales Group C2 Vehicular	13	✓	✓	✓		✓	✓		✓			✓	✓	✓			✓	✓	✓	✓	✓	✓	2D	☆	✓				✓	✓	✓	✓			✓		
L3Harris Technologies hC2 Software Suite	14	✓	✓	✓	✓			✓	✓			✓					✓	✓	✓	✓	✓	✓	2D	☆	✓				✓	✓	✓	✓		✓	✓		
L3Harris Technologies hC2 C4I Modules	15	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓			✓	✓	✓	✓	✓	✓	2D	☆	✓				✓	✓	✓	✓			✓		
Systematic Multi-Domain C2	16	✓	✓	✓	✓			✓	✓			✓	✓				✓	✓	✓	✓	✓	✓	3D	☆	✓				✓	✓	✓	✓		✓	✓		
Airbus Fortion Joint C2	6	✓	✓	✓	✓			✓	✓			✓					✓	✓	✓	✓	✓	✓	3D	☆	✓				✓	✓	✓	✓		✓	✓		
UMISOFT ECA	1	✓	✓	✓			✓	✓	✓			✓					✓	✓	✓	✓	✓	✓	2D	☆	✓					✓	✓	✓		✓	✓		
Lockheed Martin Corporation (C4ISR)	18	✓	✓	✓		✓	✓	☆	✓			✓					✓	☆	☆	☆	✓	☆	2D	☆	☆	✓			☆	✓	✓	☆	☆	✓			
Handheld Underwater Devices:																																					
Artemis Pro (with PinPoint)	3	✓	✓	✓			✓				✓		✓	✓	✓	✓						☆	2D	☆					✓	✓	✓	✓					✓
UWIS	2	✓	✓	✓			✓		✓		✓	✓	✓	✓		✓						☆	2D	☆						✓	✓	✓			✓		✓
SonaDive RTSYS	4	✓	✓	✓			✓		✓	✓	✓	✓	✓	✓		✓						☆	2D						✓	✓	✓	✓			✓		
Dive Computer Example:																																					
Ratio Computers	5		✓	✓			✓				✓				✓	✓																			✓		

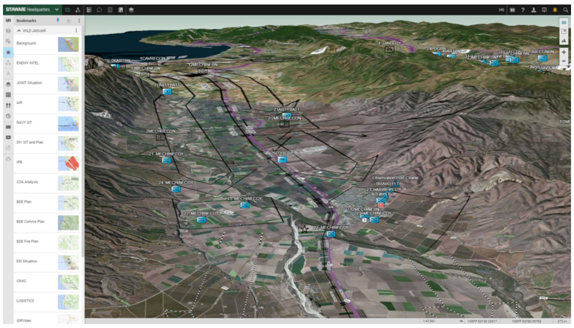

Figure 5: Example of Command and Control system utilizing 3D geospatial visualizations with appropriate military symbolgy annotations. Image source: (Richardson, 2020).

4.1 Geospatial Visualizations

Map-based Visualizations: Maps visualized in military operations have various uses, such as communicating the existence and the location of spatial features and entities, along with the distance between them. Map-based visualizations are used in almost all examples analyzed in the survey. However, only mainly utilizing 2D maps with the exceptions of General Dynamics, Systematic, and Airbus products. These exceptions provide cutting-edge 3D geospatial visualizations, using 3D maps to illustrate spatial features such as regions populated with friendly or enemy forces, or critical infrastructure targets, while communicating information regarding the variations in terrain, the altitude of natural spatial features, and the extent of vegetation and cover (DA, 2005; Usbeck et al., 2015), as shown in Figure 5. Implementing such visualization techniques with the addition of a temporal component could offer significant improvements in situational awareness, as maps allow commanders in remote and military forces "on the ground" to know where they and their allies are located, making it possible to make decisions accordingly.

Map Primitives: We define primitives as basic geometric shapes that depict spatial features, entities, or phenomena on visualized maps. These basic geometries can represent various things depending on the context (Żyszkowska, 2016). E.g., specific points on a map, in the context of military operations, could represent evacuation and rescue facilities or places to avoid. Similarly, lines can be used to represent pre-planned routes, while polygons can be used to indicate areas of interest that should be investigated or avoided. From our survey, all C2 systems utilize map primitives, making them an essential component of such systems. However, the usability of map-based primitives in such systems varies drastically, with some systems seeming unintuitive to use, such as L3Harris. Similarly, there is room for improvement in terms of conveying necessary information through map primitives by exploiting the use of visual attributes (color/hue, texture, etc.) of such primitives overlaid on a map, according to military standards, theory, and their associated meaning and intent. The map primitives are typically managed and organized in specific map overlays or layers, which we describe next.

Map Overlays: Map overlays superimpose multiple thematic maps to reveal information about specific geographic patterns of a particular subject matter (theme) in a geographic area. The ability to add overlays to a base map is an essential function in any Geographical Information System (GIS), as the ability to do so opens up the possibility of gaining a new understanding of an area based on the relationship between the different types of maps layered on top of each other (Romeo et al., 2019). In our analysis, all C2 systems implement such a component. Similarly, military symbology may be incorporated into geospatial-temporal visualizations relevant to military operations through a map overlay, as demonstrated in Figure 6. However, there is an opportunity to expand the range of map overlays offered by such systems.

Additional Military Layers: Additional Military Layers (AML) are defined in NATO standard STANAG 7170 as *"A unified range of digital geospatial data products designed to satisfy the totality of NATO non-navigational maritime defense requirements"* (NATO's Geospatial Maritime Working Group (GMWG), 2022). The data products are essentially digital datasets organized in specific map overlays and designed to meet the needs of several military organizations. AML primarily provides information related to several environmental conditions in the operating area that might affect the execution 2 of a military operation. The AML Handbook (NATO's GMWG, 2022) mentions many interesting AMLs. However, for the purposes of this survey, the most relevant military layers which could be of interest to incorporate into geospatial-temporal visualizations are:

- Maritime Foundation and Facilities (MFF)
- Routes, Areas and Limits (RAL)
- Atmospheric and Metreological Climatology (AMC)

Currently, there is much opportunity to further expand the visual integration of such military layers in almost all of the command and control systems assessed in this survey.

Spatial Comparisons: Many scenarios in military operations fundamentally rely on comparisons and representations, along with many methods of collecting and simulating data to help solve these comparison and representation questions (Kim et al., 2017). In particular, there is a shortcoming in visualizing 3D geospatial and time-varying 3D geospatial data. Geospatial 3D data can typically be represented in one of two ways: 1) "surface-based" representation and 2) "volume-based" representations. Both of these representations present data using some form of 3D computer graphics, where facilitating accurate spatial perception in three dimensions and addressing occlusion issues are typical concerns. Javed and Elmqvist (2012) propose five views for composite visualizations: Juxtaposition, Superimposition, Overloading, Nesting, and Integration, which can be used in situations where a single visualization is insufficient. Similarly, there is ample opportunity for the visualization community to integrate such methods in the domain from our analysis of C2 systems.

4.2 Geospatial-temporal Visualization

Visualizing 2D & 3D Geospatial Data Temporally: Due to advances in tracking technologies, tracking individual objects in remarkable spatial and temporal detail is possible. This inherently geospatial-temporal data availability can provide further insights into dynamic processes and challenges that traditional (static) geospatial analysis techniques cannot (Laube, 2014). Consequently, work has appeared addressing several aspects related to modeling, storing, indexing, querying, and analyzing geospatial-temporal data (Hamdi et al., 2021). In turn, the research field studying the mapping and visualization of geospatial-temporal data has also received a great deal of attention. Due to the dynamic nature of the geospatial-temporal data captured, various visualization techniques have taken advantage of this by representing the data in various ways. Visualization techniques utilize 2 and 3 spatial dimensions and the possibility of showing the progress of moving objects over time in such spaces. In addition, the option of visually encoding attributes of the object via color or texture is also accounted for temporally. As a result, many geospatial-temporal data visualization techniques have been developed and published Andrienko et al. (2010); Sibolla et al. (2016); Zhu et al. (2021). Furthermore, the existing methods have also been studied from the perspective of the types of data they can be applied to and the types of exploratory tasks they can support (see Andrienko et al. (2003)).

The use and depiction of geospatial-temporal data especially come into play in visualizing military operations in terms of representing objects and actors on a map over time. E.g., the correct application of visualization techniques in military operations through the geospatial-temporal representation of objects and actors can help illustrate to commanders the evolution of such entities' movement, which can be recorded in terms of a trajectory that can be visualized in several ways. E.g., simply as a fixed or fading trace of the continuous and true path of the moving entity sampled at discrete points in time.

For this survey, we define 4D representations as a time-series of 3D geospatial data. According to our survey, state-of-the-art implementations of these visualizations appear in General Dynamics, Systematic, and Airbus products.

Timelines: A timeline is essential for sense-making regarding how sequences of events unfold or resources are used over time. As such, they can be invaluable tools to command and tactical forces in the planning, execution, and assessment 1 – 3 of military operations. This is the case, as a timeline allows a user to examine information chronologically and identify temporal patterns and relationships. Therefore, timeline visualizations should preferably enable the interactive temporal grouping of events with the possibility to further explore underlying or associated data visually and take notes (Nguyen et al., 2014). For example, a C2 system may implement a timeline in conjunction with cartographic maps to better understand how sequences of events may unfold in military operations. While a temporal element is used in all C2 systems surveyed, the interaction potential for such a component is not realized in any examples analyzed. It represents a significant opportunity for the visualization community's input.

4.3 Visualization Interaction

In terms of interaction techniques in interactive data visualization, a specific set of high-level interactions is established in Munzner's Framework and discussed in-depth in her book *"Visualization Analysis, and Design"* (Munzner, 2014). This abstraction hierarchy categorizes high-level and low-level tasks that can be applied to the geospatial-temporal visualizations in military operations examined in this survey. E.g., actions broken down into user goals of "analyze", "search", and "query" can be applied to visualizations used in military C2 systems.

Figure 6: Example of Holographic Tactical Sandbox Augmented Reality mission preparation system implemented with relevant military graphics. Source: (Airbus, 2022).

Map-based Interactions: During the planning phase 1 of military operations, there may be a need to manage various assets or objects on a map over a period of time. This could be achieved through interaction with visualizations using geospatial-temporal data to represent these different assets or objects. As such, a commander creating a plan or various run-through options should be able to edit, delete or create/place assets using such a visualization effortlessly. Furthermore, the interaction design of such visualizations should be designed such that a plan can be edited and deleted and what-if scenarios can be readily devised. During the drawing and editing of assets/objects, the user must be able to undo and redo actions. In addition, the assets should be manageable and be allowed to be linked to a specific order. As mentioned previously, low-level actions, such as "select", "navigate", "arrange", "change", "filter", and "aggregate," could be applied in such a manner to achieve these high-level tasks mentioned above using map-based 2D or 3D interactions. All such interactions are implemented in C2 systems surveyed in the paper, making them an essential element of such information systems.

In the planning phase 1, many high-level tasks performed by a commander are carried out in a collaborative setting where different people with different roles will reason and cooperate intensively using a collaborative digital map (Figure 6). Therefore, essential assets and objects should be presented to commanders on this 2D or 3D geospatial-temporal visualization to allow suitable actions of the planning phase 1, such as to help devise a plan of action and predict resource requirements. E.g. in this case, appropriate actions may be the selection of military objects, easy navigation of the map, arrangement of military assets, adjustment of parameters, filtering of objects,

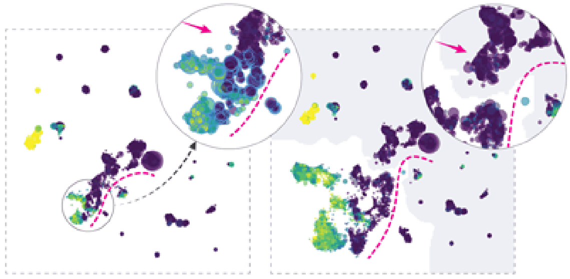

Figure 7: Image illustrating the information visualization technique of focus plus context to present information. Source: (Höllt et al., 2019).

and clustering of objects.

Map Navigation: Typical methods of achieving intuitive map navigation could be the use of "click and drag" (or "touch and drag"), "double click to zoom", "scroll to zoom", "pinch to zoom", the use of arrow keys to pan (important for accessibility), or plus and minus keys to zoom (Heyman, 2022). These basic map navigation methods are implemented across all C2 systems surveyed. Additionally, more sophisticated data-driven maps may use automatic zooming and panning when an event occurs, for example, a user selecting a region or creating a key-frame in a military plan narrative. In cases where a narrative may occur, e.g., when a commander creates run-through scenarios, key moments on a map may be presented as a narrative that is advanceable using buttons. Currently, none of the systems surveyed include such a visualization technique.

Focus+context: Focus plus context as a method of IVs enables one to see the object of primary interest presented in complete detail while at the same time gaining an overview of the surrounding information available. This technique can be a very spatially efficient method of allowing the user to view detailed information regarding spatial data. As seen in Figure 7, we can see how this visualization can be effective in representing two different types of spatial data simultaneously, effectively (Card et al., 1999). None of the visualizations in the military products examined implement such a technique, presenting another opportunity for visualization to improve situational awareness.

4.4 Collaboration

Collaboration occurs in an environment where *"participants are encouraged to use critical thinking; solve problems; and share information, knowledge,* *perceptions, ideas, and concepts in a spirit of mutual cooperation"* (DOD, 2018). As such, devices, software tools, and infrastructure that facilitates collaboration are aimed at connecting the right people and data at the right time to complete a task solve a problem, or discuss something of mutual interest. Geospatial-temporal visualizations aid this goal in the planning, execution, and assessment phase 1 – 3 of military operations.

Vital to visualizing information intended for military collaboration is the possibility to establish a COP, which is a single identical display of relevant information (e.g., maps with the position of own forces and enemy forces, position and status of critical infrastructure such as bridges, roads, etc.) shared by more than one command. A COP facilitates further collaborative planning and execution 1 – 2 and improves situational awareness across echelons.

In this survey, we use the Computer Supported Cooperative Work (CSCW) time-space matrix to group collaboration types according to Pedersen and Koumaditis (2020):

- (Temporal dimension) The interaction of users occur at the same time (synchronous)
- (Temporal dimension) The interaction of users occur at different times (asynchronous)
- (Spatial dimension) Users are co-located
- (Spatial dimension) Users interact remotely

Out of the four categories introduced by the CSCW matrix, synchronous and co-located, along with asynchronous and remote collaboration, are especially important within military organizations as synchronous and co-located collaboration can be said to happen between commanders and their staff in a command center. In contrast, asynchronous and remote collaboration can be said to occur, e.g., between commanders and military personnel "on the ground". These two types of collaboration can be said to primarily occur in the planning phase 1 and execution phase 2 of military operations.

5 DESIGN IMPLICATIONS

A design space describes possible design choices of varying utility and can be used to derive design guidelines and highlight gaps in current solutions. Developing design guidelines for VUIs used for decision support can be valuable in reducing the workload of VUI engineers. In the context of VUI design, a design space helps to understand and tackle challenges such as how to:

- Decide on the combination of visualization techniques most suitable for domain tasks.
- Compare existing visualization approaches to identify their advantages and disadvantages.

The design space this survey assembles emphasizes and covers VUI aspects relevant to designing and developing IVs and GUIs for military decision-support systems and devices used in extreme situations characterized by high uncertainty, high risk, and severe time pressure. However, the design space does not account for aspects such as data and run-time complexity, which also influences VUI design and the choice of visualization techniques. Our design space is shown in Table 1. The design space is a method for analyzing twenty VUIs of military products and connected devices selected in the survey to be compared in terms of several distinct design considerations, which can provide a basis for guidelines when implementing geospatial-temporal visualizations in this context. This design space examines the examples under the broad categories of review rank, operations process, domain-specific considerations, and types of visualizations utilized in such systems. From our analysis, several implications emerged from the design space, which we describe in the following.

Implementation of Military Standards: The use of text highlights an area for potential improvement across all products. Most of the examples (except some C2 systems) in our analysis do not strictly adhere to and utilize the relevant military standards in terms of text. Improvements in this area could offer benefits such as increased legibility, consistency, and familiarity with military personnel across products used in military operations. Furthermore, improved adherence and implementation of text according to relevant military standards could result in decreased cognitive load and the possibility of more quickly gaining a COP and increased consistency across products and nations.

A similar observation can be made regarding color, where most products do not appear to utilize color according to the relevant military standards to their maximum potential. Using color according to relevant military standards could increase usability, decrease cognitive load and increase responsiveness amongst military personnel.

According to our analysis, symbology, as a category of analysis, suggests the most significant potential for improvement. Strict compliance with relevant military symbology standards is rare. Similarly, there is much scope for improvements in terms of using metaphors and semiotics in iconography used in the different products. Implementing such improvements would lend itself to increasing the usability of the products. Furthermore, it would improve cohesiveness and reduce the cognitive load of using such products.

Map-based Primary Visualizations: Our analysis of map-based primary visualizations has highlighted that there may be a disparity in functionality between systems that utilize map-based primary visualizations in command and control products and those used in C2 systems, handheld devices, or small alternative devices. As such, our analysis has highlighted the potential to increase map-based primary visualization capabilities in such devices. For example, such advancements in map-based primary visualizations in smaller devices may be achieved by increasing map overlay and primitive capabilities, increased use of micro-visualizations, or AR head-mounted devices. Furthermore, there is a broad scope for improvement by increasing spatial comparison capabilities, for example, through juxtaposition. This is also true for enabling multiple layers for additional military layers, which would similarly increase the capability and effectiveness of primary visualizations in such devices.

Time-based Geospatial Primary Visualizations: Primary visualization capacity could be improved by extending timelines linked to geospatial visualizations. Including such time-based visualization techniques could enhance military personnel's ability to run through what-if scenarios, better understand how operations play out over time and replay analysis and assessment 3 of operations.

Alternative & Micro-visualizations: The analysis of other methods of primary visualizations found that, overwhelmingly, spatial visualization methods were the predominant alternative method of displaying primary visualizations. Furthermore, data glyphs and word-scale visualizations were not utilized in the analyzed examples. However, using micro-visualizations might be an avenue worth pursuing in future research. Particularly in military sub-sea operations, they may be of great value to handheld and smaller alternative devices such as dive computers.

Secondary Visualizations: Our analysis found no robust trend regarding secondary graphics used in the examples analyzed, as examples utilize a broad range of secondary graphics, including diagrams, images, and data visualizations. Our analysis, however, found that using images in smaller devices may be a valuable development and innovation.

Interaction: In the analyzed examples, there was a wide and consistent use of interaction methods, including map-based interactions, visualization linking, and information dashboards utilized in all examples except the smallest analyzed example. However, our analysis did identify that while most examples use a wide range of interaction techniques, only some of the analyzed examples employed the focus plus context interaction method. The focus plus context interaction makes it possible to display essential data at the focal point at full size and detail and display the area around the focal point (the context) to help make sense of how the critical information relates to the entire data structure. This interaction method may greatly benefit military operations and, as such, be considered for implementation in future research.

6 CONCLUSIONS

Through the lens of visualization concepts and theory, this survey examined several academic studies related to military theory and situational awareness, as well as twenty examples of modern military products, to gain an understanding of the types of geospatial-temporal visualizations that military organizations use. Some examples highlight novel geospatial-temporal visualization methods, e.g., (Airbus, 2022), which incorporate emerging technologies such as AR, 4D geospatial visualization, and holographic tactical sandbox simulation appropriately to suit the high-level tasks of the domain. However, many of the examples examined in this survey fall short of this endeavor for lack of appropriate consideration of the domain-specific constraints, which include environmental constraints, display size, input devices, and suitable graphic design. With these factors in mind, additional research must be conducted to assess further geospatial-temporal visualization solutions used in military products. The design space we provided is based on analyzing academic literature and studying twenty relevant military products. We aim to further use the results of this research as a well-grounded foundation to share and grow knowledge on geospatial-temporal visualization techniques used in the military domain.

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